Numerical parameter characterisation of a buried mine blast event with further emphasis on IED shapes and soil bed conditions

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Abstract: The modelling of a buried charge and its impact on vehicle structures is a complex simulation task since numerous structural variables, physical properties and numerical parameters have to be determined to provide accurate estimation of the structure's response. A number of variables in question are directly related to the numerical approach chosen to perform the analysis while others relate to the overall modelling process and the detail used to describe the physical processes. This paper documents the results of a comprehensive sensitivity study of the structural response of a vehicle subjected to the impulse from a buried charge using the discrete particle method (DPM) to model the soil and high explosive (HE) coupled to a finite element solver for the structure. Fourteen design variables and numerical parameters were studied requiring in excess of 1000 computational hours. The response parameter was chosen to be the total blast impulse (TBI) on the structure. The non-linear transient dynamic explicit finite element solver used for the analysis was the IMPETUS Afea Solver® which has implemented the DPM for blast simulations and is called iDPM. The study includes soil characteristics and charge related parameters. The depth of burial (DOB) and number of discrete particles were also considered in the study. As a natural extension of the sensitivity study the effect of an improvised explosive device (IED) made from an oil can is investigated as well as the effect of having rocks in the soil bed making it a non-homogeneous soil bed.

Keywords: explicit finite element; mine blast; IEDs; improvised explosive devices; the IMPETUS Afea Solver®; soil; high explosive; sensitivity study.

Reference to this paper should be made as follows: Jensen, M.R. and Smith, W. (2019) 'Numerical parameter characterisation of a buried mine blast event with further emphasis on IED shapes and soil bed conditions', *Int. J. Vehicle Performance*, Vol. 5, No. 4, pp.377–408.

Biographical notes: Morten Rikard Jensen graduated from Aalborg University, Denmark in 1995 with a Master degree in Manufacturing Engineering. He obtained his PhD and Doctor Europeus in Mechanical Engineering at the same University in 1999. The work included research at Linköping University, Sweden. From 2001 to 2012 he worked at LSTC, USA. The last seven years as Support and Trainings Manager in charge of all support at LSTC. He authored the official Getting Started with LS-DYNA book. Since 2012, Dr. Jensen has been the CTO at CertaSIM, LLC, the official distributor of the IMPETUS Afea Solver®. His work covers many different applications such as mine blast, ballistics, composite, car crash, metal forming, water ditching, sports applications, biomedical simulations etc.

Wilford Smith received his BS in Mechanical Engineering from the Georgia Institute of Technology in Atlanta, GA in 1979 and his Masters in Mechanical Engineering from the University of Michigan in Ann Arbor, MI in 1980. After graduation he worked as a Member of the Technical Staff at AT&T Bell Laboratories until 1981 when he joined SAIC. At SAIC he has developed modelling and simulation technology for projects ranging from design of supersonic combustion systems to development of hybrid power systems for series and parallel automotive propulsion systems. Current activities include applying high-resolution computational mechanics tools to the design of ground vehicle occupant safety systems.

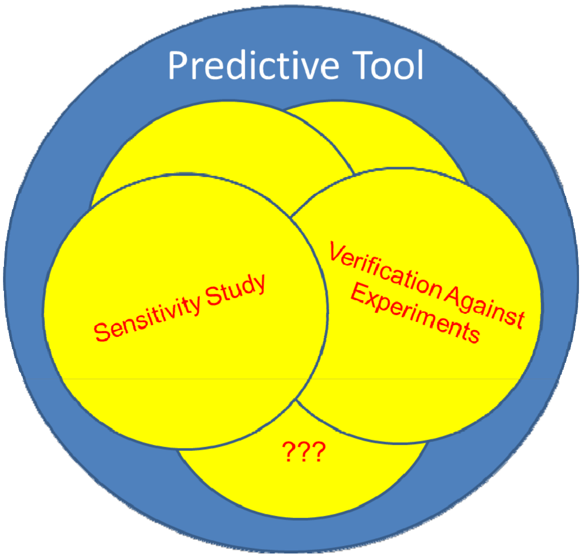
This paper is a revised and expanded version of a paper entitled 'Discrete particle method is a predictive tool for simulation of mine blast – a parameter study of the process and approach' presented at *2015 NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS)*, Novi, Michigan, 4–6 August, 2015.

1 Introduction

A large percentage of casualties in recent military conflicts are due to blast from buried mines, typically coming from improvised explosive devices (IED). Of the 2820 US combat fatalities resulting from "Operation Enduring Freedom-Afghanistan" between 2001 and 2017 nearly 50%, 1407 fatalities, were caused by IED's (icasulties, 2017). The design of better vehicle protection systems is necessary to reduce the number of casualties due to IEDs. At the heart of the design process is simulation technology which allows engineers to test and refine their ideas in a virtual environment before the costly step of building a prototype for physical testing. It is of vital importance to have accurate predictive numerical tools for this process to minimise the number of physical tests. A predictive simulation tool for a specific application area requires verification against experimental data and understanding the limits of validity of the simulation tool as depicted graphically in Figure 1. Of critical importance in developing confidence in the predictive ability of a simulation tool is verification and validation against subscale experiments. In this case the physical and numerical parameters used in the software are calibrated against subscale tests using simplified geometries and physical situations. The parameters developed during the validation and verification process are then used as the base for prediction of more geometrically and physically complicated scenarios with limited or no supporting experiments. Tuning of numerical and process parameters against available experimental data is a necessary condition for the software to be

predictive, however, the limits of applicability of the tuned parameters and the sensitivity of the results to the parameters must also be ascertained. This condition leads directly to the second condition that must be performed to consider a numerical model a predictive analytic tool, namely, a sensitivity study of both the process parameters and the numerical parameters. A sensitivity study gains knowledge about the response of the numerical model and helps in the model calibration phase as well as determining the stability limits of the software.

Figure 1 Necessary prerequisites to consider when evaluating if a software program is a predictive tool (see online version for colours)



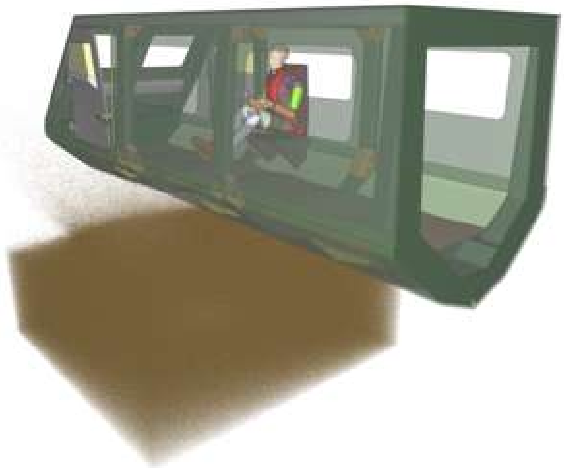
In this paper the discrete particle method (DPM) provided in the IMPETUS Afea Solver® (iDPM) is applied for modelling the mine blast event. IMPETUS is an explicit non-linear transient dynamic Finite Element solver. The iDPM module is described in detail in Børvik et al. (2011), Mindle et al. (2014) and Wadley et al. (2013) where the approach was verified against mine blast experiments. The module was also successfully applied in Holloman et al. (2015). The benefit of the iDPM method is further enhanced when combined with a solver that takes full advantage of GPU Technology for massively parallel processing. IMPETUS has been shown to accurately simulate mine blast during the last ten years, both by researchers and in commercial projects. An extensive number of experimental blast tests have been simulated. This means that the IMPETUS Afea Solver® satisfies the first prerequisite of being a predictive software tool.

The benefit to using the iDPM is its high degree of accuracy for modelling soil, air and HE. The parameters for a HE are calibrated for a particular explosive based upon a standard cylinder test (Børvik et al., 2011). Similarly the soil parameters have to be determined as well but the variation of soil type does not include a simple list as the characteristics of the soil are affected by moisture content, level of compaction and the soil make up, e.g., sand, dirt, rocks, etc. (Bergeron et al., 1998; Ehrgott, 2010; Ehrgott et al., 2011; Fiserova, 2006; Grujicic et al., 2009, 2013). The procedure to calibrate the soil model requires a good understanding of how the various iDPM parameters influence

the resulting blast load on a structure. The best way to explain this is with a sensitivity study, which is the second prerequisite for obtaining a predictive simulation tool and one of the main purposes of this study.

The model of the TARDEC Generic Vehicle Hull along with the IMPETUS Afea Hybrid III 50th Percentile Blast Anthromorphic Test Device (ATD) model is illustrated in Figure 2. More details about the calibration of the ATD for crash worthiness and blast can be found in Jensen (2017) and Jensen et al. (2017). The hull model was chosen for the parameter study omitting the ATD as it does not significantly influence the blast loading. It is a particularly relevant structure to use for the study as it is a real structure that has been blast tested by the US Army and continues to be used by TARDEC to better understand how to protect the warfighter.

Figure 2 IMPETUS model of the TARDEC generic vehicle hull (see online version for colours)



The IMPETUS Afea Solver® utilises GPU technology for massively parallel processing which results in a simulation time of only 9 h for the Base Model. If the IMPETUS Blast ATD is included, the computational time is around 12 h.

For the sake of the discussion presented in this study, the total blast impulse (TBI) on the structure was chosen as the response parameter and numerical results are compared with the 'Base Model' shown in Figure 2 including the ATD. The Base Model is described in Section 2.2.

With the confidence gained from the sensitivity study more complex simulations were carried out to obtain knowledge about the mine blast event. First, a simulation of a more realistic shaped IED is performed where the explosive for the IED is contained in an oil container. This is more common than the cylindrical shape and other simple geometries used in the sensitivity study. Secondly, the effect of a non-homogeneous soil bed is investigated. Several different scenarios of rocks embedded in the soil are shown. It is seen how the soil moves differently and what influence it has on the TBI.

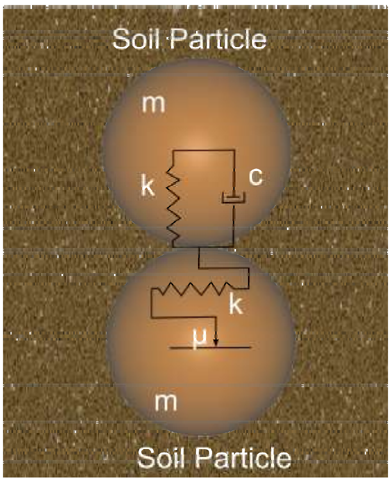
2 Base model results and design space for sensitivity study

Modelling blast events with the iDPM is very straight forward in IMPETUS. It is done with the *PBLAST command where domains are defined for the soil, HE and air (if used). By simply specifying the total number of particles the solver automatically calculates the correct ratio between the domains. The solver has built-in packing algorithms for the domains in which Lagrangian structures can be embedded easily by simply including a part ID in the part set of the structural parts that interact with the particles. Furthermore, friction can be specified for the interaction between the soil and the structure.

The modelling of HE is done with rigid spheres that have elastic impact for inter-particle contact. The implemented approach is described in Børvik et al. (2011). In addition to predefined HE's that have been calibrated in subscale experiments by the developers of IMPETUS such as C4 and TNT one can also define a HE through the input parameters. The coordinates of the detonation point within the HE domain is defined by the user.

The soil is also modelled with discrete rigid particles but the inter particle contact includes both friction and damping. The rheological model for the soil is illustrated in Figure 3, showing the springs and the damper. The normal and tangential spring constants are given the same value.

Figure 3 The applied rheological model for the soil. The springs have stiffness *k* and the damper has a damping coefficient *c*. The particle mass is m and an inter particle stiffness is given by μ (see online version for colours)



The soil is packed using a unit cell with periodic boundaries that makes it possible to repeat the geometry to generate the Soil Bed. These unit cells are then scaled which affects the inter particle stiffness which becomes $k = L/L_0 \cdot k_0$ where L is the scaled size of the unit cell, L_0 is the un-scaled size and k_0 is the stiffness of the un-scaled unit cell. The details of the implementation are shown in Børvik et al. (2011) and Mindle et al. (2014).

As with the HE, the soil can also be specified using built-in calibrated models for dry or wet soils. Because of the variability of soil and soil bed configurations, it is recommended that one calibrates the soil based on a blast test of a rigid flat plate using

the soil bed that is to be used for the more complicated structure. This will require using the "user defined soil option" which is straight forward to specify. It includes the soil density, the soil particle stiffness, the soil particle friction and damping. For dry soil, stiffness and friction is used and for wet soil, stiffness and damping. A detailed description of the procedure for soil calibration can be found in Jensen (2014). The set-up in the command file requires only a few lines as illustrated in Figure 4.

Figure 4 The *PBLAST command is used for defining the blast set-up (see online version for colours)

*PBLAST

entype, enid, air, material, he, N_p, c_{dec}, deform

bc_{x0}, bc_{x1}, bc_{y0}, bc_{y1}, bc_{z0}, bc_{z1}, μ, $pfac$

gid_{glob}, gid_{mat}, gid_{he}, x_0, y_0, z_0, t_0, t_{end}

pack, ρ_s, k_s, μ_s, ξ_s — used if material = user

ρ_{he}, e_{he}, γ_{he}, v_{he}, D_{he} — used if he = user

Source: IMPETUS (2018)

2.1 Design space

It is always a challenge to define the experimental matrix or the design space when a sensitivity study or optimisation is carried out. In fact, the design space often changes during the study due to unknown constraints on the design variables or physical limitations on the process parameters. Based on the experience and interest of the authors, 14 design variables were chosen related to both numerical and process parameters. For each of the design variables between three to five or more variations where tested, leading to around 80 entities in the design space, each representing a numerical simulation. Fewer could of course have been selected but the knowledge obtained will be very helpful in future work in the field of mine blast simulations. The following characterisation of the parameters illustrates the base for the design space:

- *Soil*: Density, packing routine, inter particle stiffness, inter particle friction, inter particle damping, soil domain size and friction between structure and soil.
- *Charge*: Charge size, geometry, HE type, orientation (angle), off centre location, DOB.
- *General*: Total number of particles.

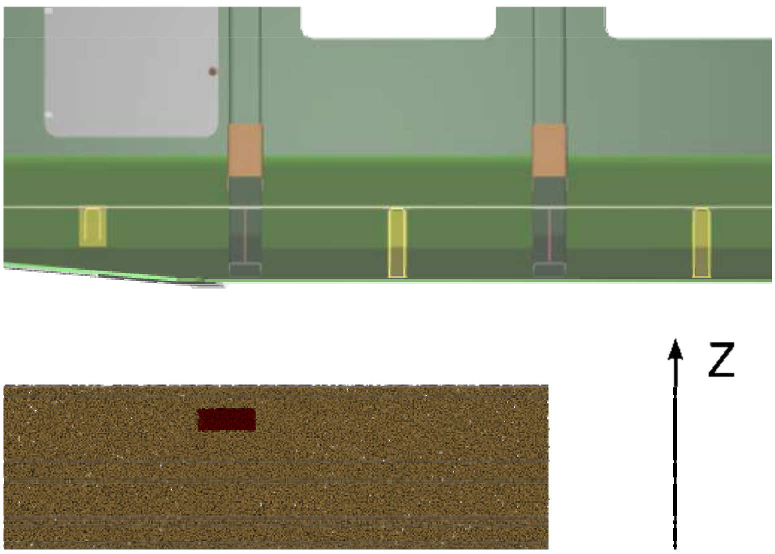
Each of the design variables and their settings are described in Section 3. The total blast impulse (TBI) on the structure in the global Z-direction was chosen as the response parameter. The global Z-direction is shown in Figure 5. TBI is a very common measure in a blast event, and clearly indicates the design variables sensitivity and influence on the response. The TBI, is the impulse intensity multiplied by the face surface normal (n_x, n_y, n_z) and then integrated over the surface of the body. This means that the TBI has a direction and a sign. It can be negative or positive. The units for impulse in the SI system are [N·sec]. The impulse intensity is basically the pressure integrated in time with a unit of [Pa·sec] in the SI system. Thus, the TBI is given by:

$$\text{Total Blast Impulse (TBI)} = -\int_A \text{Impulse Intensity}\begin{pmatrix} n_x \\ n_y \\ n_z \end{pmatrix} \mathrm{d}A \qquad (1)$$

2.2 Base model

The Base Model is the TARDEC Generic Vehicle Hull model which is modelled as a full 3D model using solid elements for all components, even for the welds and bolts. IMPETUS predominantly works with higher order elements, that is, elements with non-linear shape functions that accurately handle bending and are less prone to shear or pressure locking. All higher order elements in IMPETUS are fully integrated and, hence, do not suffer from zero energy modes (hourglassing). Traditional high order elements are not well suited for dynamics or large-deformation problems with Lagrangian meshes, see Belytschko et al. (2000, p.456). Extreme dispersion destroys their ability to handle propagating waves and high eigenfrequencies on the element level have a severe impact on the critical time step size. The set of high order elements (quadratic and cubic) in IMPETUS use special interpolation functions that do not suffer from the above-mentioned shortcomings. IMPETUS's high order elements are called the ASET™ Family of Elements. In the Base Model only quadratic elements are specified as they are more than sufficient to accurately model the structure. A total of 24,902 elements are used. It took approximately three days to mesh and setup the model for the first simulation. A section cut of the Base Model is shown in Figure 5, where the discrete particles for the soil and HE also can be seen. The total count of particles is 4,000,000 distributed as 3,977,497 for the soil and 22,503 HE particles.

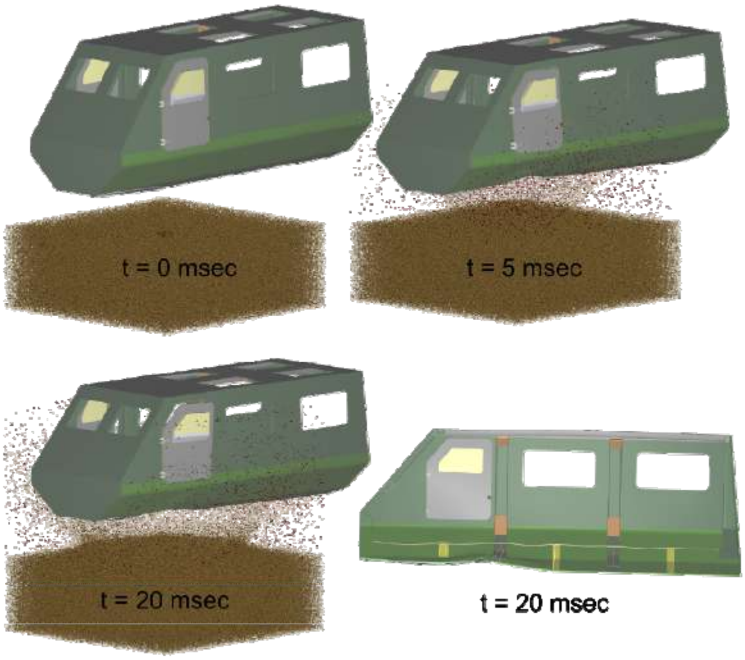
Figure 5 Section cut of the base model showing the structure, soil and the high explosive (see online version for colours)



The HE is a cylindrical 8 kg C4 charge with a height to diameter ratio of 1 : 3 and a DOB of 4 inches. It is placed in the centre of the structure widthwise and in the front lengthwise as seen in Figure 5. No air particles are included in the Base Model. It has been shown that air has no influence on the results for a buried mine as discussed in Caippi (2016). The simulation time is set to 20 msec. The soil density is taken from (Williams and McClennan, 2002) and their experimental set-up is modelled and the soil is calibrated against their experimental response parameter in Jensen (2014) which are the values used in the Base Model. This leads to a soil density of 2301 kg/m^3, a soil friction of 0.25 and a soil stiffness of 5e+8 N/m. The soil is assumed dry so the soil packing routine number 3 is applied which generates 10,000 soil particles per unit cell. The soil packing routines are explained in Section 3.1.

The result of the Base Model simulation is shown in Figure 6, where a large deformation is seen. The floor is “rippled” and the doors bend.

Figure 6 Simulation results from IMPETUS. It is seen that at 20 ms the doors are bending and the floor ‘rippled’. The last picture is a section cut to see the damage of the floor (see online version for colours)



A time history plot of the TBI on the structure in the global Z-direction is shown in Figure 7 and it is found that the maximum value is 21,705 N·sec. The direction of global Z is illustrated in Figure 5. This value will be used for comparison in the sensitivity study.

The geometry of the model is symmetric about one plane and one could have taken advantage of this to save computational time if the loading was symmetric too. However, the study includes cases where the loading is off centre so to be able to compare the results it was necessary to run the full 3D model. For future cases where the ATD is included, the geometry would definitely not be symmetric. The Base Model was

modelled with half symmetry and the TBI history plot is verified against the full model, showing agreement and consistency, see Figure 8. The computational time was 4 h 42 min illustrating the benefit of applying symmetry when appropriate.

Figure 7 The total blast impulse on the structure in the global Z-direction for the base model throughout the simulation. The global Z-direction is illustrated in Figure 5 (see online version for colours)

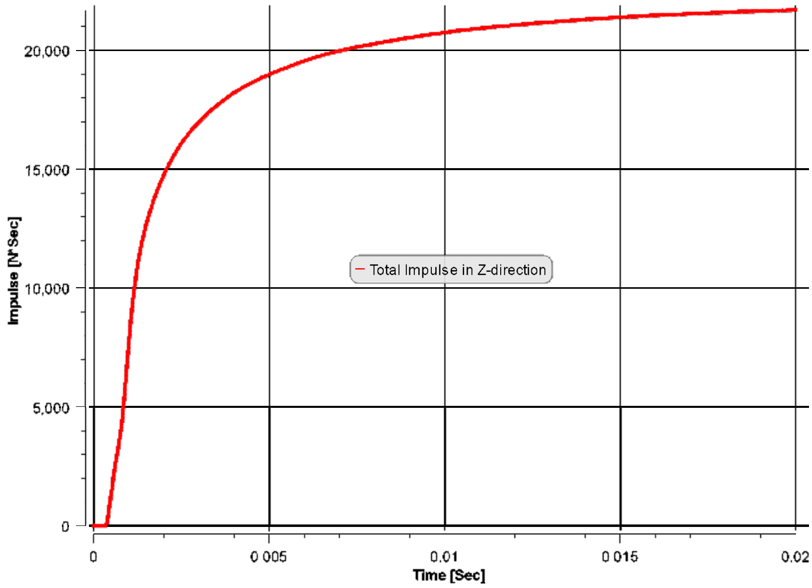
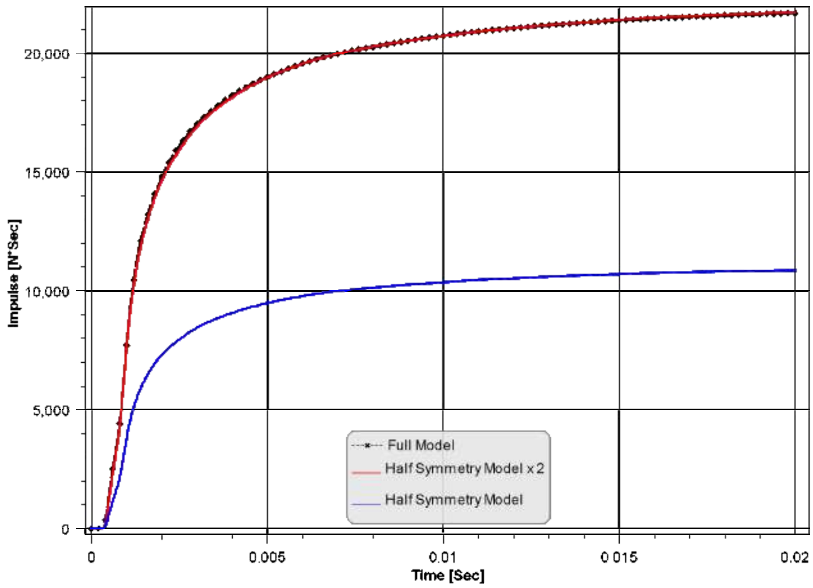


Figure 8 The TBI on the structure in the Z-direction for the Base Model during the simulation showing results for both full and half symmetry models. Note that the results for the half model need to be multiplied by two in order to obtain the impulse for the whole model (see online version for colours)



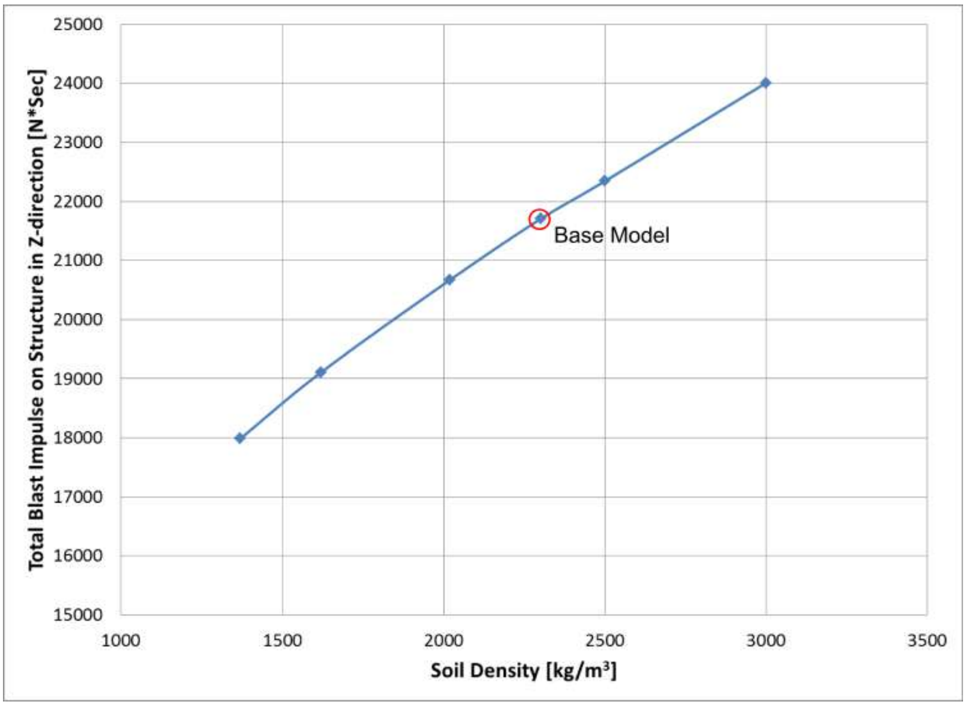
3 Numerical results from sensitivity study

The simulations were run on various hardware platforms which included the NVIDIA K40 GPU for parallel processing. The same version of the solver was used for all simulations. The design variables are grouped into the following three main categories: Soil, Charge and General.

3.1 Soil parameters

The first parameter investigated is the density of the soil, the Base Model used 2301 kg/m^3. The values tested are 1370, 1620, 2020, 2500 and 3000 kg/m^3. The wet and dry built-in soil has the density of 2020 and 1620 kg/m^3, respectively. The density of 1370 kg/m^3 is listed as the density for 7% moisture content in Anderson et al. (2010) and Anderson et al. (2011). The last two densities are specified to see the effect of heavier soil. It is expected that the TBI will increase with increasing density. The results are plotted in Figure 9 where this is verified but it is also observed that there is a linear relationship between the soil density and the total TBI on the structure. This seems reasonable when only density is changed.

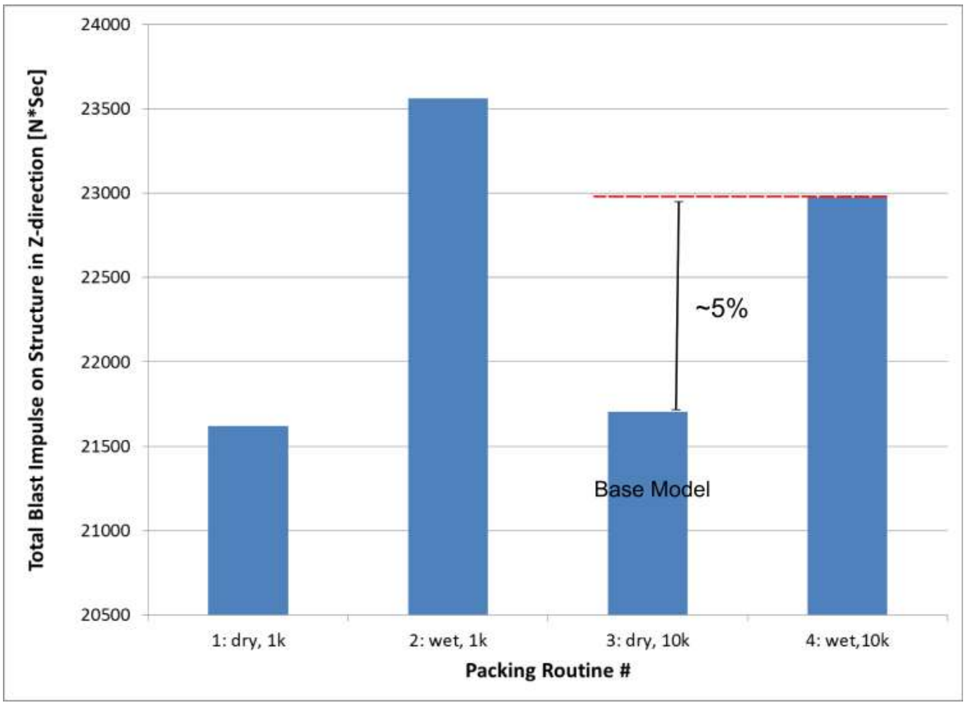
Figure 9 Influence on the blast impulse from changing the soil density (see online version for colours)



The Base Model used dry soil with the soil packing method number 3. The soil is packed in unit cells with periodic boundaries as discussed earlier and in Børvik et al. (2011) and Mindle et al. (2014). It was chosen in Jensen (2014) to use a dry packing routine and calibrate based on the friction. The main difference in the packing method is the number

of particles included in the unit cell and the grain radius. The older methods, 1 and 2, used 1000 particles in each cell and the newer ones, 3 and 4, use 10,000 per cell. All include wet and dry packing options, where the wet soil option has a larger grain radius than the dry. Using 10,000 particles per cell is more accurate and is the recommended choice. It is expected that the wet soil will give the largest impulse and this is clearly verified in Figure 10. Note that there is a smaller difference between the two dry packing options than with the two wet options, which is around 2%.

Figure 10 Influence on the blast impulse from the different packing routines (see online version for colours)

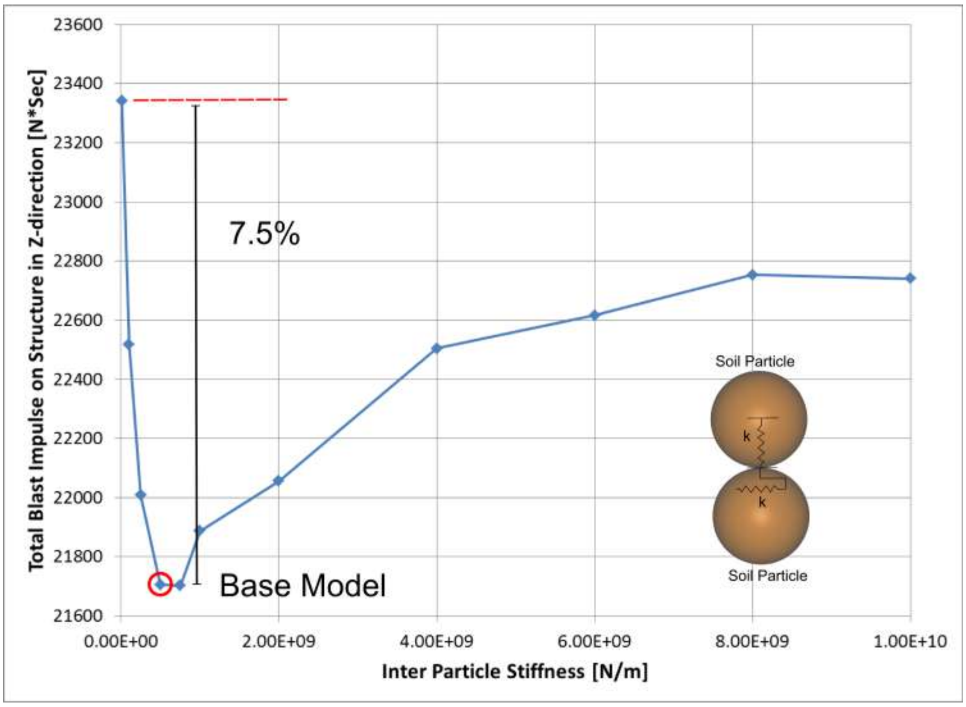


It is recommended to use the newer more accurate packing options rather then select the wet or dry soil options. Thus, one needs to calibrate the soil. In the Base Model, the difference between the new wet and dry packing options is around 5%.

As mentioned there are tangential and normal springs between the soil particles and the same stiffness is used for both. For the built-in soil a stiffness of 4e+8 N/m for the dry soil and 4e+9 N/m for wet soil is used. The Base Model uses 5e+8 N/m based on the author's experience and it has also been the experience that the stiffness value does not have a strong influence on the results, unless it is changed by an order of magnitude. This is true when considering TBI or peak deflection of the target. However, research in progress indicates that the stiffness seems to have an influence on the slope of the centre deflection curve in a blast plate test (Jensen et al., 2018). In the sensitivity test, values of 1.e+8, 2.5e+8, 7.5e+8 and 1e+9 N/m were tested. These values represent the stiffness of the unit cell, k_0, as mentioned earlier. The results are plotted in Figure 11, supporting

the assumption that within the same magnitude, the soil-to-soil stiffness gives similar results. The difference between the minimum and the maximum TBI value is 7.5% where the maximum value is found at the low end of the values investigated for the stiffness.

Figure 11 Influence on the TBI from the inter particle stiffness (see online version for colours)



Based on these results, calibration of the soil was done using 5e+8 N/m for dry soil and 5e+9 N/m for wet soil.

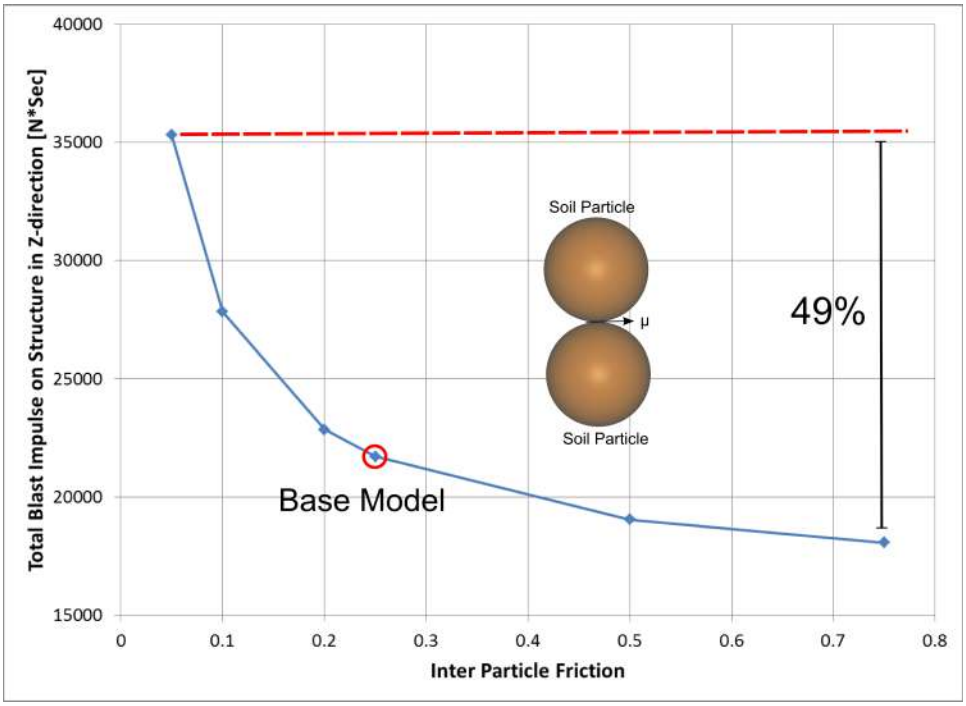
The friction between the particles is one of the most important parameters for the soil specification and thus often used as the main calibration variable, especially since soil density is a standard parameter that can be easily measured. For the built-in soil models, the dry soil has a friction of 0.1 whereas there is no friction applied for wet soil. The values tested here were: 0.05, 0.1, 0.2, 0.25, 0.5 and 0.75 where 0.25 is the one used for the Base Model. The influence from the setting of the friction coefficient on the TBI is seen in Figure 12. By increasing the friction the impulse is lowered and it should be noted that the maximum difference in the TBI is a decrease of 49% showing the importance of carefully setting the friction value.

Experience shows that one seldom has to go outside the range that is shown in this series of runs. The number of iterations for calibrating the friction and thus the soil depends on what is an acceptable error when comparing to the target value, a small percentage error is acceptable.

As mentioned damping between the soil particles can also be applied and this is done for the built-in wet soil but not the dry option. The value used was 0.005. To test the influence from the damping coefficient, a total of six test cases were selected.

They are split into two main groups, one using packing routine 3 (dry, 10k) and packing routine 4 (wet, 10k). It is expected that the results for packing routine 4 will result in a higher TBI than using packing routine 3, this is based on the study of the routines as shown earlier. This was indeed the case and it is further seen that the TBI in both cases drops with increased damping values as shown in Figure 13. The maximum decrease for packing routine 3 is 2.7% when compared with the Base Model.

Figure 12 Influence on the TBI from inter particle friction which has been found to be an important soil parameter (see online version for colours)



The soil particle interaction with the Lagrangian structure is treated with a contact routine that is implemented into the *PBLAST command so the user does not define a contact specification but only needs to provide which parts will be in contact with the particles. One can simply specify ALL to consider all Lagrangian parts in contact. Though there is no *CONTACT command, it is possible to set a friction coefficient for this contact and the influence of this on the TBI has been tested. The Base Model does not have any friction included for the particles in contact with the Lagrangian structure. As shown in Leonards (1965), the friction coefficient can be rather large but we have often used 0.3 and the experience is that the parameter does not have a strong influence on the TBI. In this series, friction coefficients of 0, 0.05, 0.1, 0.2, 0.3 and 0.5 are tested. The results are shown in Figure 14, illustrating a nearly linear relationship where it should be noted that specifying no friction and a friction coefficient of 0.5 results in only a 6% difference in the TBI.

Figure 13 Influence on the TBI from setting the damping between the soil particles for different packing routines (see online version for colours)

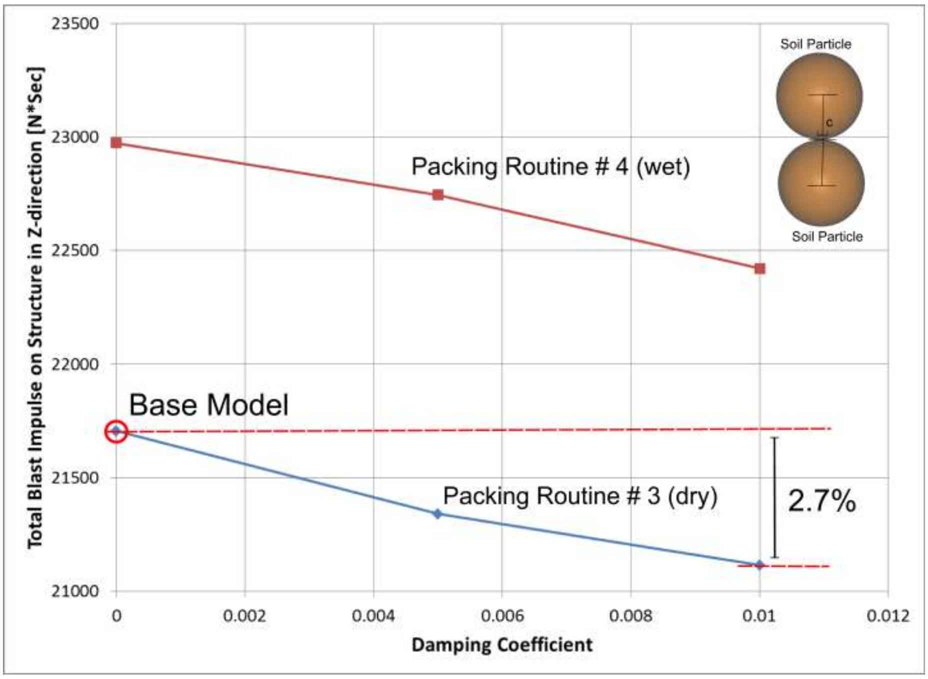


Figure 14 Influence on the TBI from setting the friction between the soil particles and the structure (see online version for colours)

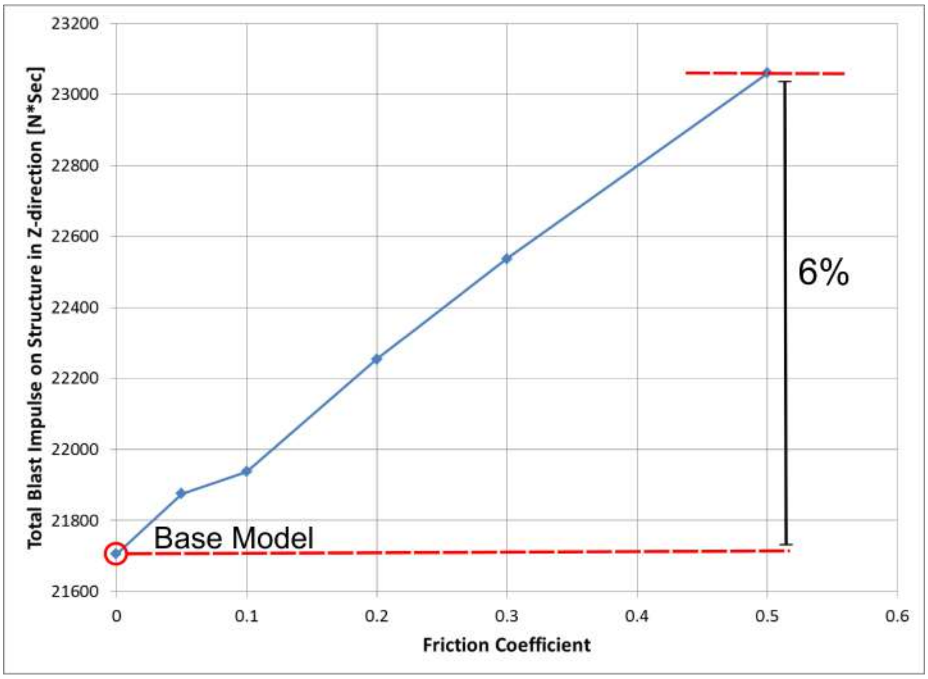
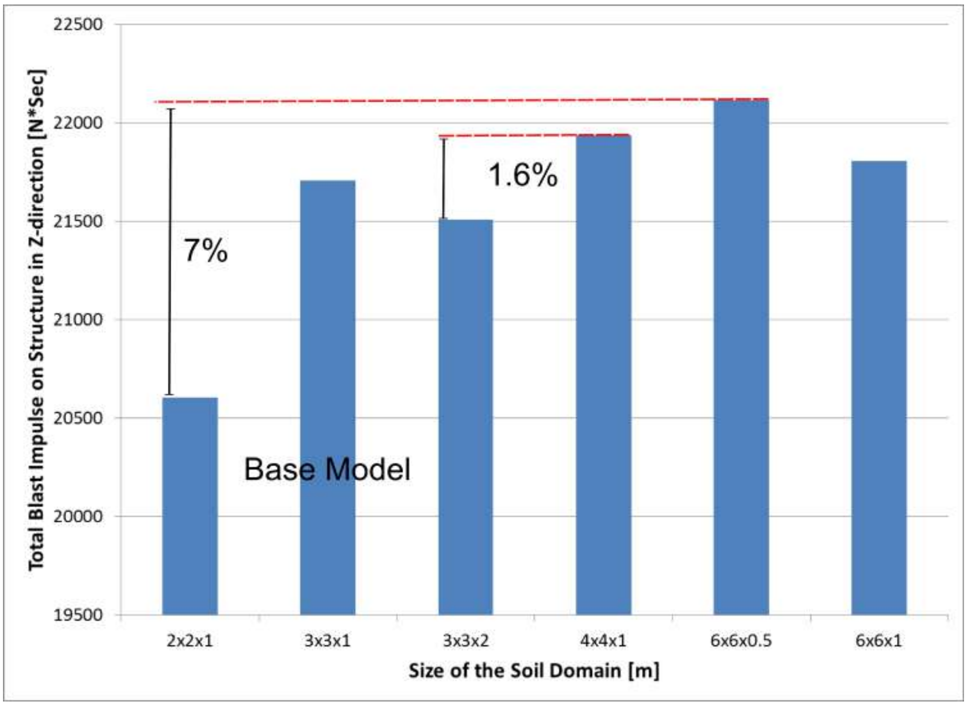


Figure 15 The various tested soil bed dimensions and their influence on the TBI (see online version for colours)



One parameter that is not mentioned often in the literature is the size of the Soil Bed. In NATO (2011) the recommendation is a minimum of 2×2 m of soil around the charge for the given charge but no information is given about the depth. In Assaf et al. (2014) a soil bed of 2×2 m with a depth of 1.6 m is applied for a 2 kg TNT cylindrical 1 : 3 charge. In the Base Model a $3 \times 3 \times 1$ m soil bed is used. Five other tests where done with different dimensions, these are shown in Figure 15. A special version of IMPETUS was compiled for this sensitivity study since the number of HE particles should remain the same and the size and mass of the soil particles should be similar. Thus, the ratio between the volume of the tested dimensions and the volume of the Base Model was used to find the number of soil particles that should be specified. The special version of IMPETUS allowed the input of individual input to be specified for the number of particles for air, HE and soil. Of course by doing this, there is a risk of violating the distribution functions between the different particle domains. Also, the global domain needed to be changed to capture the new soil domains. The results of changing the soil bed dimensions are shown in Figure 15. The difference in TBI from the smallest value ($2 \times 2 \times 1$ m) to the largest value ($6 \times 6 \times 0.5$ m) is approximately 7%. The $2 \times 2 \times 1$ m domain is probably too narrow, having fewer particles impacting the structure and hence a lower TBI, especially considering that the width of the Generic Hull is around 1.5 m. The $6 \times 6 \times 0.5$ m domain gives the largest TBI which could be due to the use of the rigid reflecting boundary option at the bottom of the soil bed which indicates that the depth is too small. Visually, this was shown by observing the soil deformation. If these two cases are omitted, $2 \times 2 \times 1$ m and $6 \times 6 \times 0.5$ m, the difference between the maximum and

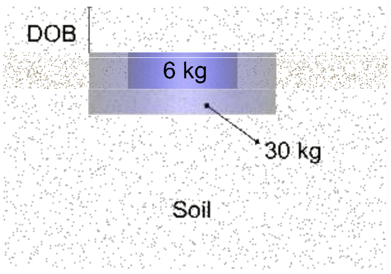
minimum values is 1.6%. The results show that the applied soil bed for the Base Model ($3 \times 3 \times 1$ m) is the minimum recommended dimensions for the investigated set-up.

The preceding discussion focused on the size of the soil bed assuming a homogeneous soil bed without rocks. In Section 5 rocks are embedded in the soil bed and different scenarios are modelled, illustrating the effect of the rocks.

3.2 Parameters for the charge

The charge size used in the Base Model is 8 kg C4 which is the size given as a STANAG 4569 Level 3 threat type in NATO (2012). In this standard the charge sizes for the different threat levels are 6, 8 and 10 kg. These are also the charge sizes listed in NATO (2011), though for both standards the charge type is TNT. In the defense community there seems to be a need for modelling larger charge sizes, mainly due to the use of more powerful IED's. A major problem in the numerical simulation of large charges is the high deformation of the Lagrangian structure since traditional linear elements cannot withstand this large deformation. Thus, by applying a large charge size it shows the influence on the TBI but it is also a good validation of the ASET™ element technology. Five different charge sizes were tested besides the Base Model: 6, 8, 10, 15, 20 and 30 kg. This means that the largest charge tested was three times the maximum threat level defined by the NATO standards. The DOB was kept the same as well as the diameter to height ratio. The buried 6 kg and 30 kg charge geometry is illustrated in Figure 16.

Figure 16 The smallest (6 kg) and the largest charge (30 kg) applied in the test series. The DOB was kept the same in all cases as was the diameter to height ratio (see online version for colours)



The impulses are plotted in Figure 17 where it is seen that the TBI varies linearly with the charge size. A linear relationship between charge size and TBI is also observed in Gharababaci et al. (2010) and Pickering et al. (2012), though in both cases experiments with smaller charges were considered. In Snyman and Reinecke (2006) a linear relationship is obtained with charges from 1 kg up to 6 kg.

All models ran succesfully to normal termination and there where no problems with the elements, even for large structural deformations. The Base Model has no damage or failure specified so the Hull simply bulges up as shown in Figure 18 which is the result for the largest charge size of 30 kg C4. It was seen that the integrity of the elements were intact.

Figure 17 Influence on the TBI from the size of the charge. The smallest charge is 6 kg and the largest is 30 kg, all HE are C4 (see online version for colours)

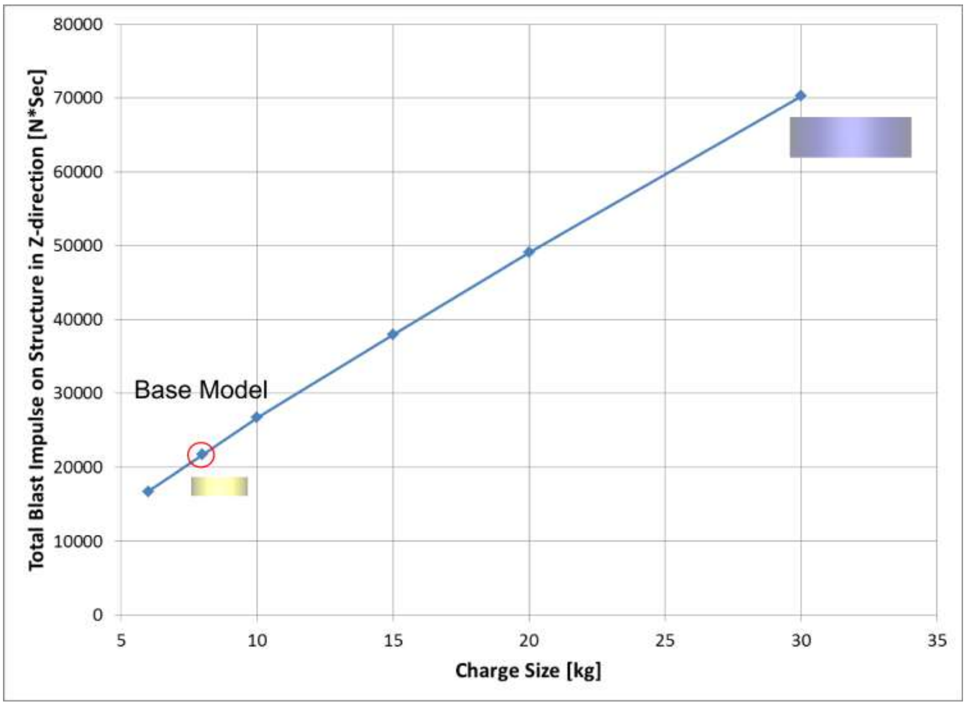
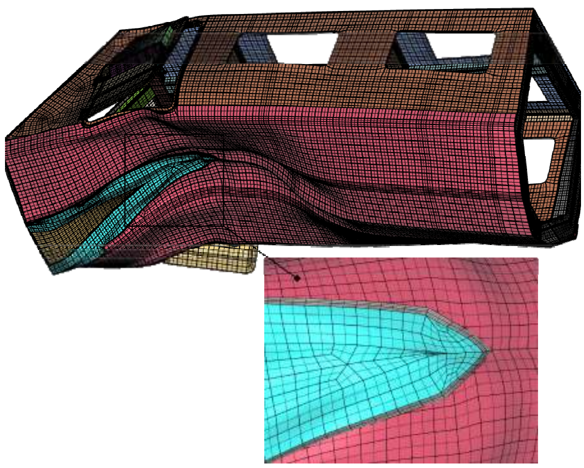


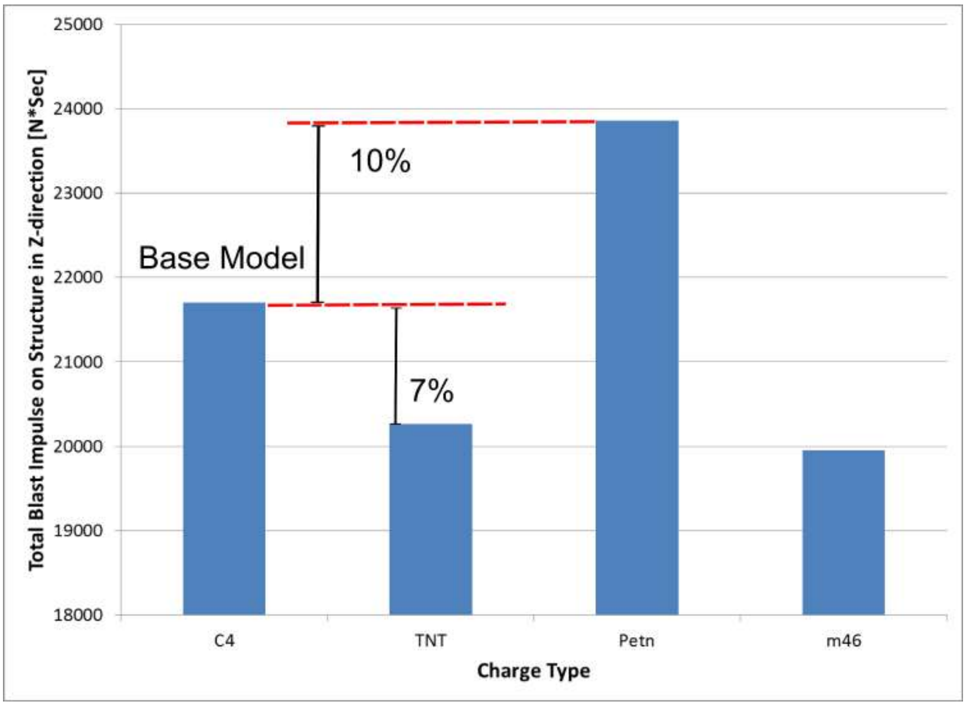
Figure 18 The deformation of the structure for a 30 kg charge. It is seen that the ASET™ elements can withstand large deformation and still keep the integrity of the element (see online version for colours)



Currently in IMPETUS there are 15 pre-defined choices for the type of HE including C4, TNT, Petn, CompB, etc. In addition a user defined HE can be specified, e.g., if LX 17 is used. A describtion of calibrating of the user defined HE can be found in Jensen et al. (2016). In this sensitivity study, four of the pre-defined HE are chosen for testing.

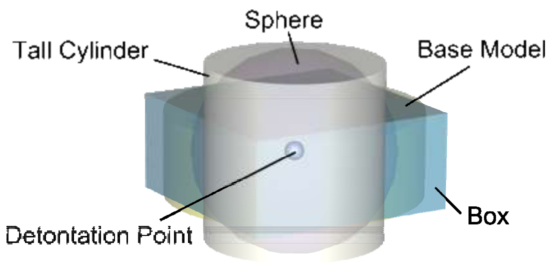
These are C4, TNT, Petn and m46. Petn is the most powerful of the selected pre-defined HE but is seldom used in large quantity. After Petn is C4 the most powerful HE, followed by TNT. M46 is a Swedish HE that is similar to TNT. Simulations have been done with all four types where the only parameter changed is the ‘*he*’ in *PBLAST which means that the volume is the same in all four cases and since the density is different for various HE, the total mass is different. The TBI results are shown in Figure 19 verifying the order of efficiency for the various types. Petn gives the largest TBI, followed by C4 with around 10% difference. The impulse for C4 is approximately 7% larger than the impulse for TNT which is very close to the response of m46. In Bergeron and Tremblay (2000) experiments with C4 and TNT are carried out showing simular results, that C4 produces a larger impulse than TNT.

Figure 19 Influence on the TBI from the type of High Explosive. Petn is the most powerful HE, followed by C4 and TNT (see online version for colours)



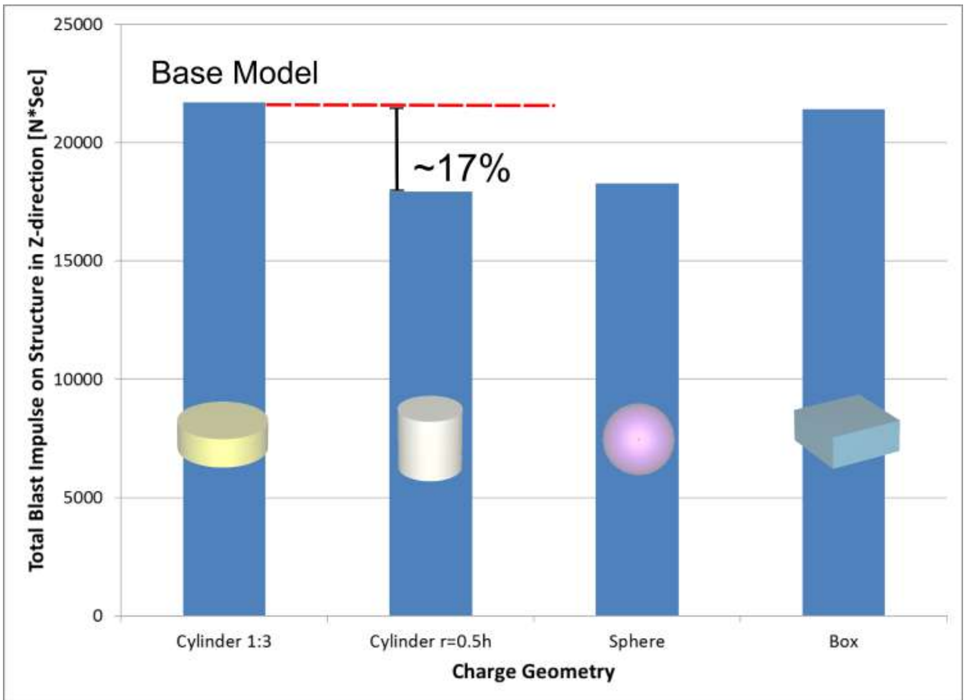
In the defense industry it is very common to use a cylindrical charge with a height to diameter ratio of 1 : 3. This is also what is applied in the Base Model. However, it would be natural that the shape of an IED would differ from a cylindrical geometry, though the cylindrical ratio is assumed to give a rather large TBI compared to other shapes. In fact in Zeleznik et al. (2015) which shows a picture of the many found and cleared IED’s it can be seen that they have many different shapes; as example an oil can. In NATO (2014) a spherical shape was prescribed which is in contrast to NATO (2011). In addition three others geometries were tested. These are a cylinder with a larger height which is the same as the diameter, a sphere and a box. They are created such that the volume is the same as the cylinder for the Base Model, thus the same charge size is applied. The detonation is at the centre of the geometry which is shown in Figure 20, together with the geometries.

Figure 20 Geometrical shapes tested for the HE. The volume for all geometries is identical and the detonation point is at the centre (see online version for colours)



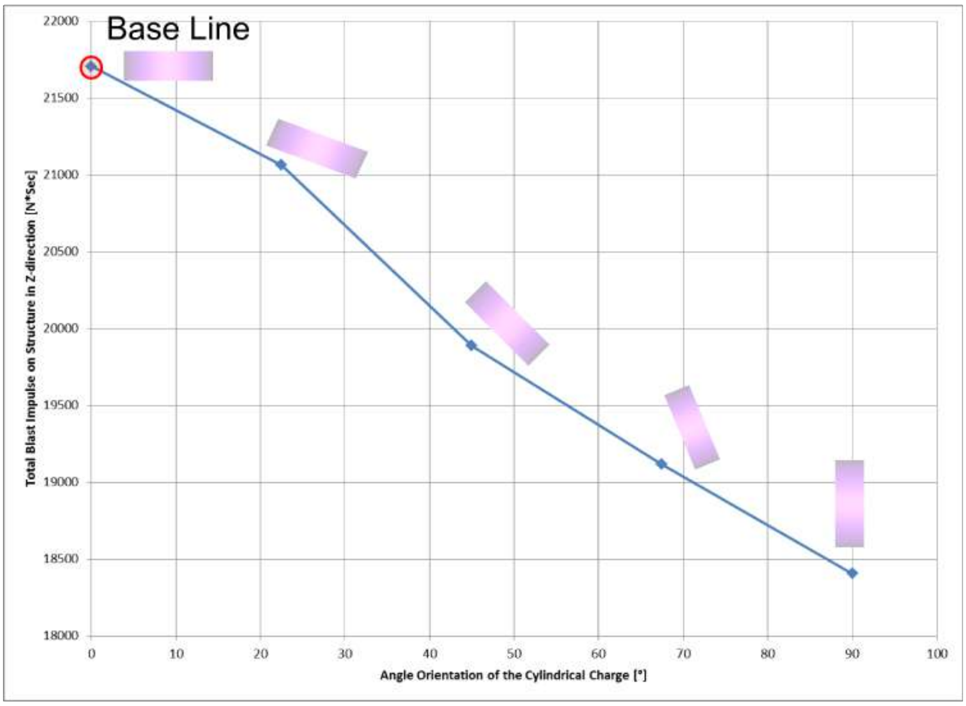
The results are shown in Figure 21 where the largest TBI was for the Base Model and the smallest impulse was when using a cylinder where the diameter was the same as the height. The difference between the two impulses was approximately 17%. In Reincke et al. (2008) it was also observed that a smaller height to diameter ratio gives a lower impulse as observed here. From Figure 21, it is shown that the shape can have a significant influence and it is important to choose the worst case scenario, which in this case is the Base Model.

Figure 21 Influence on the TBI from the geometric shape of the HE. The volume for all geometries is identical and the detonation point is at the centre (see online version for colours)



The traditional orientation of the cylindrical charge in a mine blast simulation is to have the largest surface parallel with the ground surface. This is expected to have largest TBI on the structure. To test this the charge was rotated by 22.5° between 0° and 90° so a total of four additional sensitivity runs were made. The orientations are shown in Figure 22, where the results are also plotted. It was confirmed that 0° gives the largest TBI and a vertically placed charge (90°) gives the lowest. The difference between the vertical and horizontal charge (0°) was an increase of 18%.

Figure 22 Influence on the TBI from the orientation of the HE charge (see online version for colours)



As mention earlier, the charge in the Base Model was placed along the centreline, lengthwise and within the first 1/3 of the structure. Three other locations for the charge were tested. Two of them are along the side and the last one was close to the centre but offset a little. All charges were kept in the same Z-plane and only moved in the X–Y plane in order to keep the same DOB. The detonation point was changed to reflect the new position. The locations are shown in Figure 23, where the results are plotted. It is seen that the two outer placed charges, 1 and 2, give a similar response, where the values only differ by 0.25%. Furthermore, it can be seen that the Base Model centre charge results in the largest TBI which was approximately 45% larger than the effect from the two side blast tests, 1 and 2.

Figure 23 Influence on the TBI from the location of the HE charge (see online version for colours)

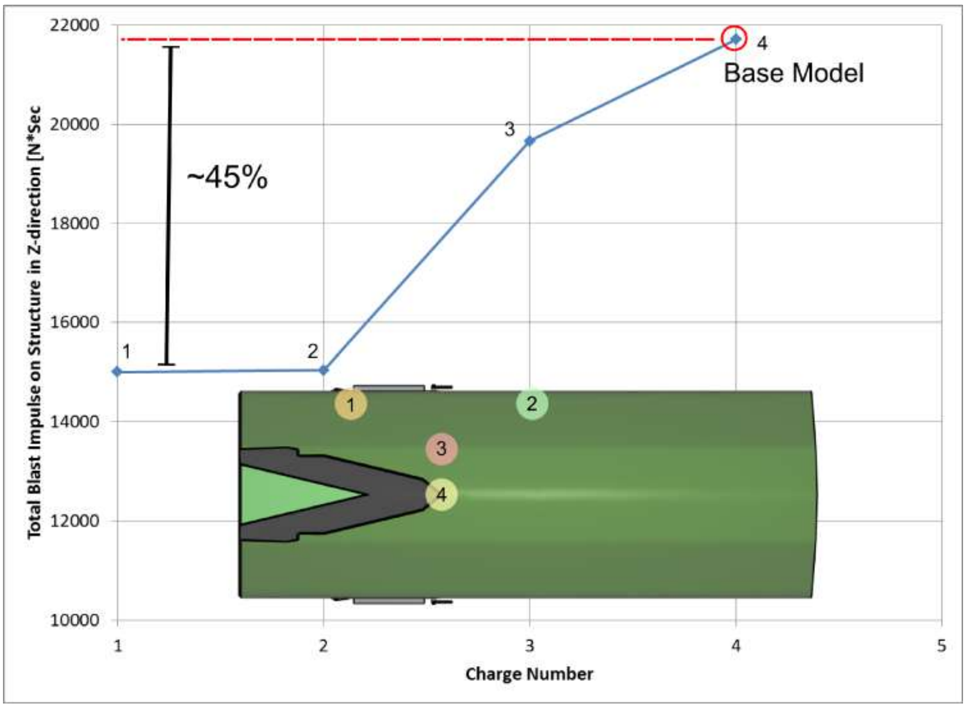
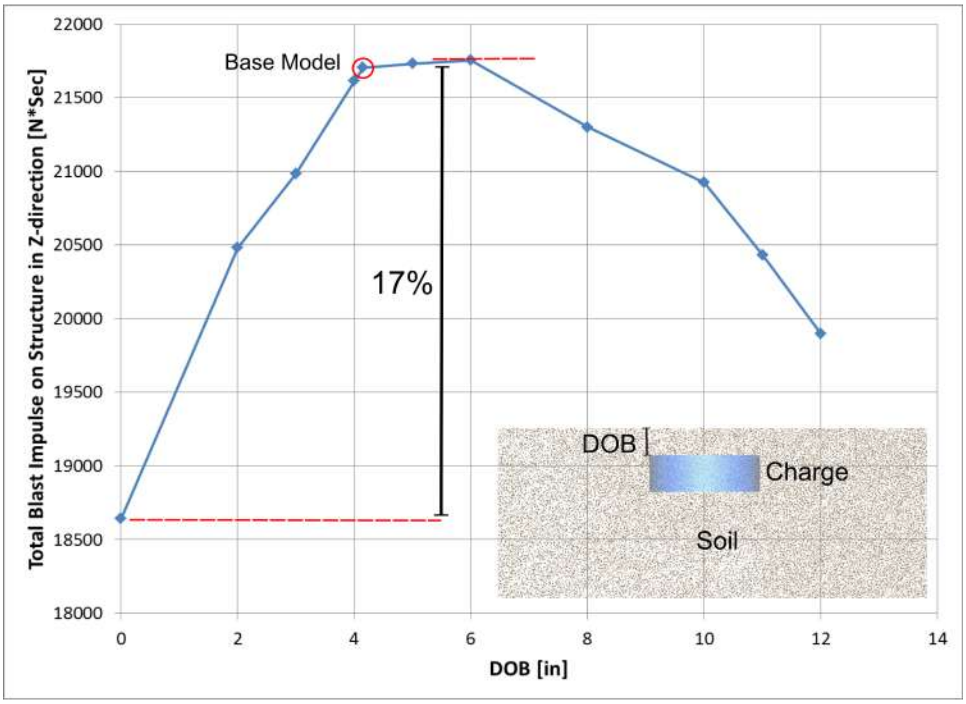


Figure 24 TBI results for different DOB of the charge (see online version for colours)

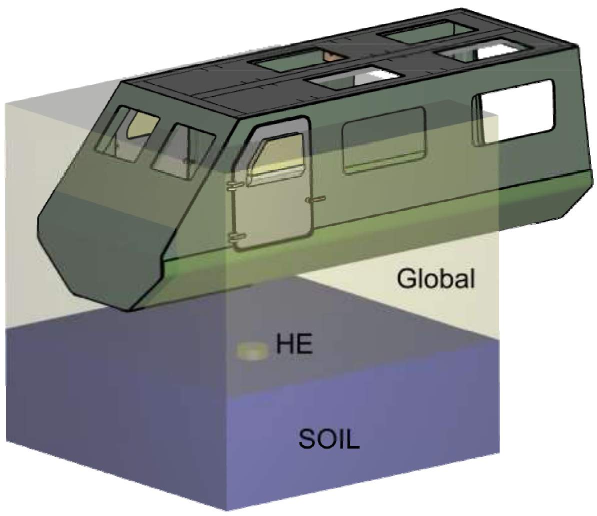


The charge depth is one of the main parameters in the mine blast event. The DOB affects how much soil will impact the structure and since the soil is the major part of the TBI for a buried mine, changing DOB can significantly change the damage. Eleven different distances have been tested as shown in Figure 24 where the definition of DOB is shown. The results show that for the cases investigated a maximum effect was obtained for DOB's between 4–6 inches. A smaller DOB results in less soil hitting the structure and thus a smaller impulse. For a mine where the top is flush with the ground level air needs to be included. After the maximum range, the charge is too deep to move the soil for impact with the structure. The difference between the smallest TBI and the largest was around 17%.

3.3 General parameters

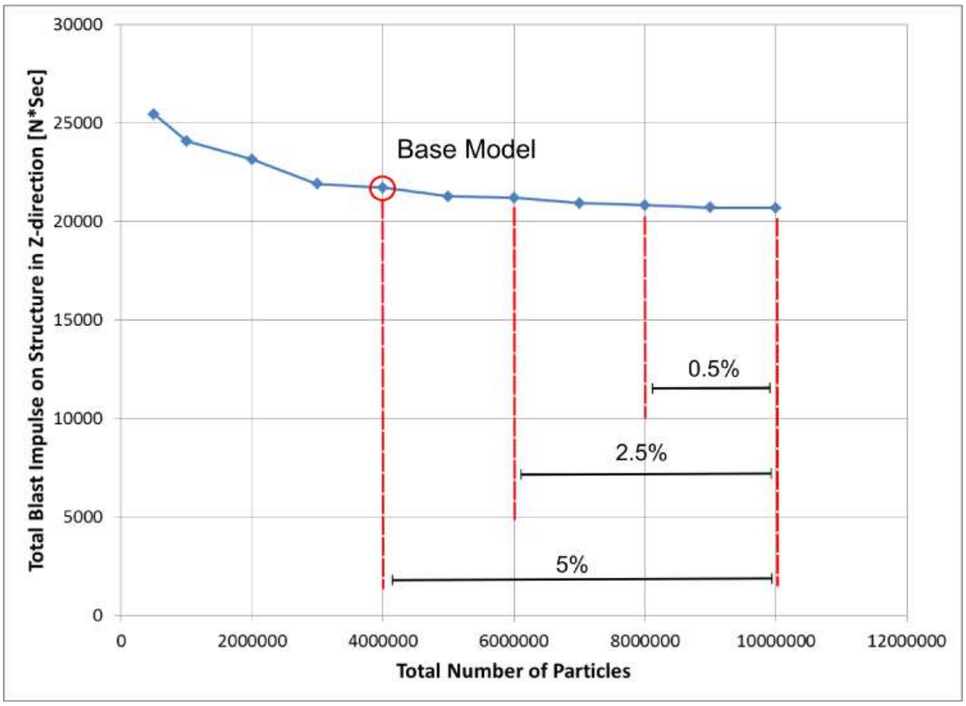
IMPETUS only requires input for the total number of particles which then covers all three DPM domains, soil, HE and air (if necessary). IMPETUS automatically distributes the particles between the domains. The number of particles can significantly change the results but in general the number is not changed often once it is determined for a specific application. It of course depends on whether the model uses symmetry and air. If the latter is used, a larger amount of particles will need to be specified since the air domain is typically large. The Base Model has 4,000,000 particles specified which is a common number used for a full model but notice that the domains do not cover the whole structure. The domains are shown in Figure 25.

Figure 25 The domains for the Base Model. Global, HE and soil domains are given. Notice that the global domain includes the other domains and only covers the necessary part of the structure (see online version for colours)



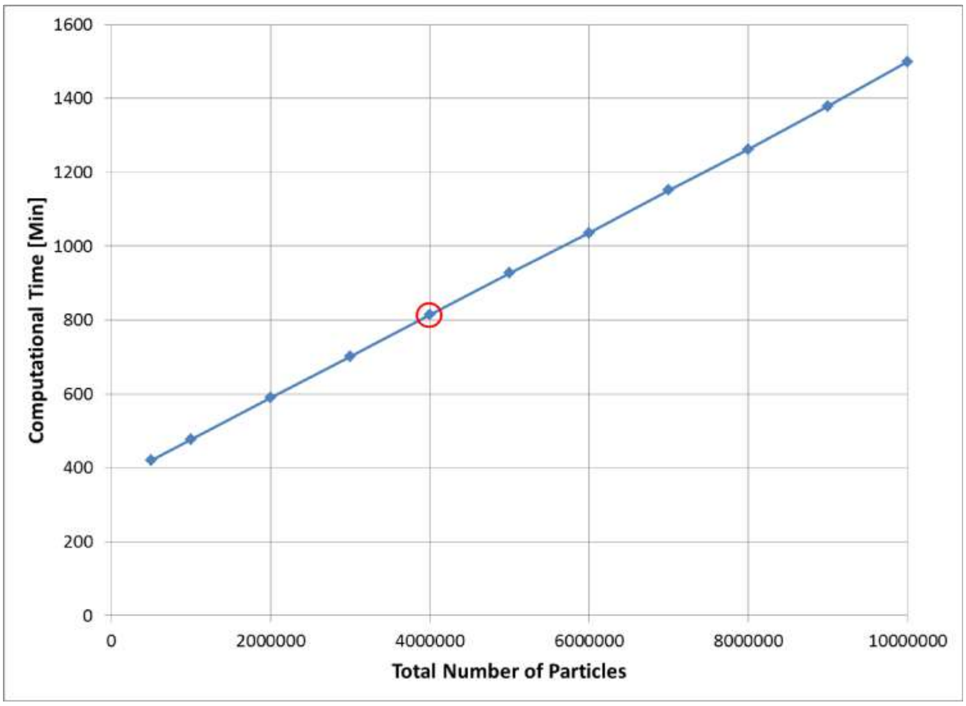
As a mesh convergence study always should be done for a Lagrangian mesh when simulating a new set-up, a convergence study of the number of particles should also be done. If too few particles are used, heavier particles will impact the structure and thus a larger TBI will be generated. It is also very useful to see a contour plot of the TBI on the structure, if it shows spots as opposed to a smooth surface, then the number of particles should be increased. In this study 11 different values were used, ranging from 500,000 to 10,000,000 particles. The results are plotted in Figure 26. A clear convergence is seen by increasing the number of particles. For the Base Model, TBI results for the 10,000,000 particles are approximately 5%. If 6,000,000 particles are used, the difference is 2.5% and for 8,000,000 it is around 0.5%.

Figure 26 Influence on the TBI from total number of particles. A clear convergence is obtained (see online version for colours)



The number of particles to use in a particular situation is, of course, a tradeoff between compute time and accuracy. For the calculations presented here the computational time is a linear function of the number of particles as shown in Figure 27. As shown on the graph it is nearly 50% more computationally expensive to use 10,000,000 particles rather than 6,000,000 particles. However, the difference in TBI between the two calculations is only 2.5%.

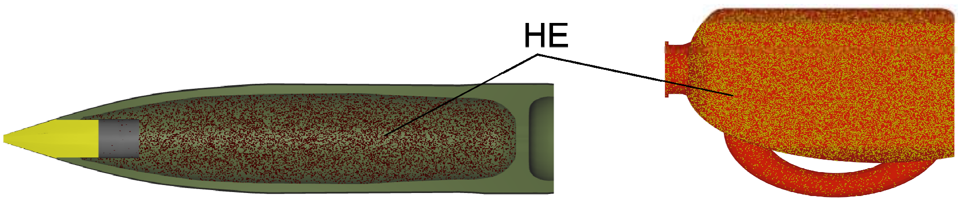
Figure 27 Computational timing depending of the total number of particles. Note that the simulations were carried out on a slower machine than was used for the original base line run so the Base Model was run again to get a comparable timing (see online version for colours)



4 Modelling realistic IED shapes

As discussed in Section 3.2 many IED’s are not cylindrical in shape but can have many different forms, such as cooler boxes or artillery shells, etc. In Rasico et al. (2016) an IED made of a 155 mm M795 artillery shell was investigated including modelling fragmentation of the shell. In Figure 28, the artillery shell is shown together with another non-standard IED, an oil can. Earlier it was found, Figure 22, that the orientation of the IED influences the blast impulse. Thus, the oil can was orientated so that the largest surface is aligned with the structure, with the expectation that it will result in the largest impulse, see Figure 29.

Figure 28 Common shapes of IED’s, here an M795 artillery shell and an oil can (see online version for colours)



The oil can is filled with HE and is scaled to contain 8 kg C4 in order to compare directly with the Base Model. The location of the oil can under the TARDEC Generic Hull is shown in Figure 29.

The development of the blast event is illustrated in Figure 30.

The maximum total impulse is 21,921 N·sec which when compared with the Baseline of 21,705 N·sec illustrates an insignificant difference between the effect of geometry when having an oil can and a cylindrical charge.

Figure 29 Location of the oil can IED under the TARDEC generic vehicle hull (see online version for colours)

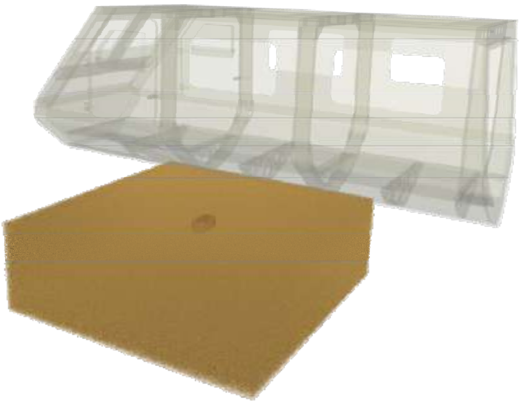
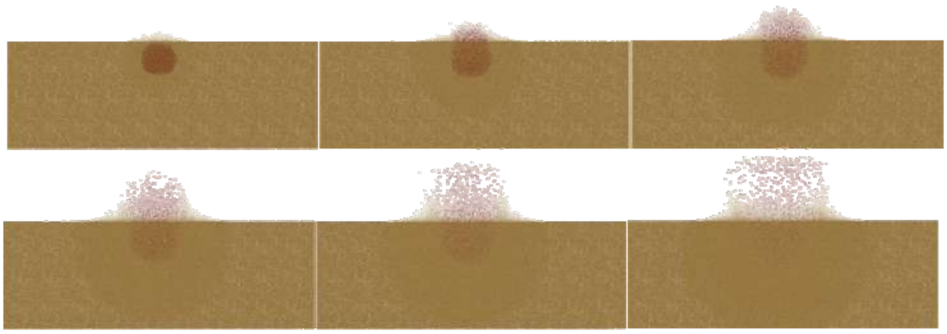


Figure 30 The development in the blast event when an oil can is used as an IED (see online version for colours)



5 Effect of non-homogeneous soil bed

So far only homogeneous soil beds have been considered but it is interesting to investigate what would happen to the blast impulse if rocks where to be embedded in the soil. To the author's best of knowledge, no open literature exists on this topic. With the use of the iDPM to model the soil it is straight forward to simulate. Several different scenarios were tested; small rocks, many rocks and one large rock placed in different locations. Two simulations with more than one rock were carried out and the initial set-ups are shown in in Figure 31.

Further tests included models with only one large rock with a mass of approximate 47 kg. Four different scenarios of this were carried out as illustrated in Figure 32. The difference in the models is the location of the rock. One is close to the front of the structure, another one is close to the back. The third model has the rock over the HE and the last one is a set-up where the rock is placed under the charge.

Figure 31 Different set-ups for non-homogeneous soil beds with multiple rock formations (see online version for colours)

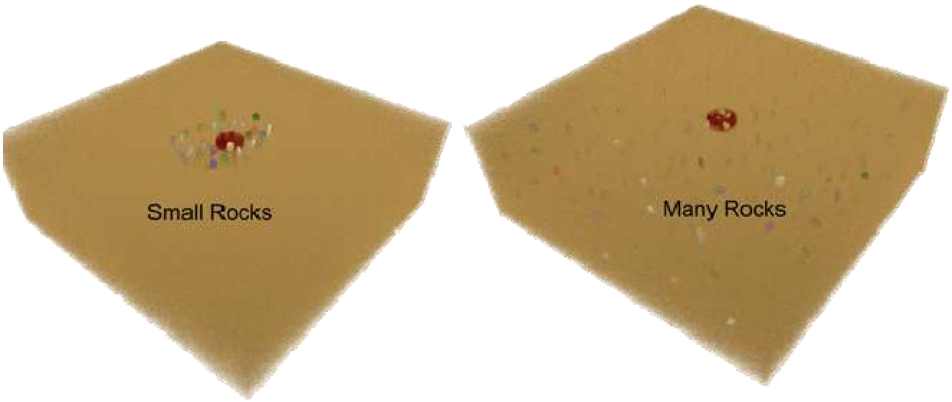


Figure 32 Different locations of a large rock in the soil bed (see online version for colours)

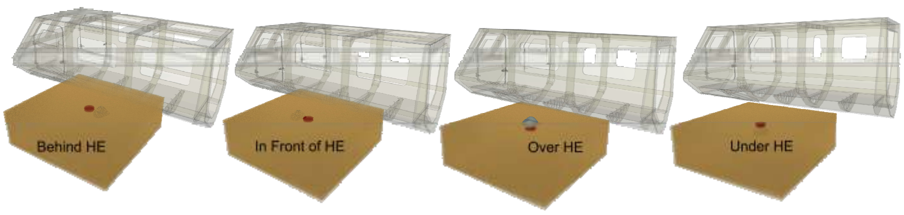


Table 1 summarises the scenarios and Figure 33 shows the results for the Maximum TBI.

Table 1 Description of the different scenarios

Model ID	*Description*
I	Little rocks with holes for the HE. There are a total of 79 rocks
II	There are 300 stones in the soil bed. They are located all around the HE
III	Large rock behind the HE
IV	Large rock in front of the HE
V	Large rock over the HE and some part of it is exposed over the soil surface
VI	Large rock under the HE

It is seen from Figure 33 that the TBI on the structure in the Z-direction is very close, except in two cases, model II and model V. Model II is the scenario where there are 300 rocks in the soil bed and hence energy has to be expected to move them and not the soil.

A large rock over the HE is the set-up for model V which results in the smallest blast impulse. Again, significant energy will be needed to move this large rock. Since it is the maximum total blast impulse that is plotted for each case, the impact from the rocks on the structure is not considered in this plot. However, significant damage to the Hull can result from the rock impact. In order to get a real indication of the survivability of the Hull the deformation should be investigated. Figure 34 shows the deformation for the Base Model, model II and model V.

The figure clearly illustrates that the structure was significant deformed by the large rock, though the TBI was only around 60% of the value obtained for the Base Model.

Figure 33 Influence on the blast impulse from embedding rocks in the soil bed. The description of each configuration is listed in Table 1 (see online version for colours)

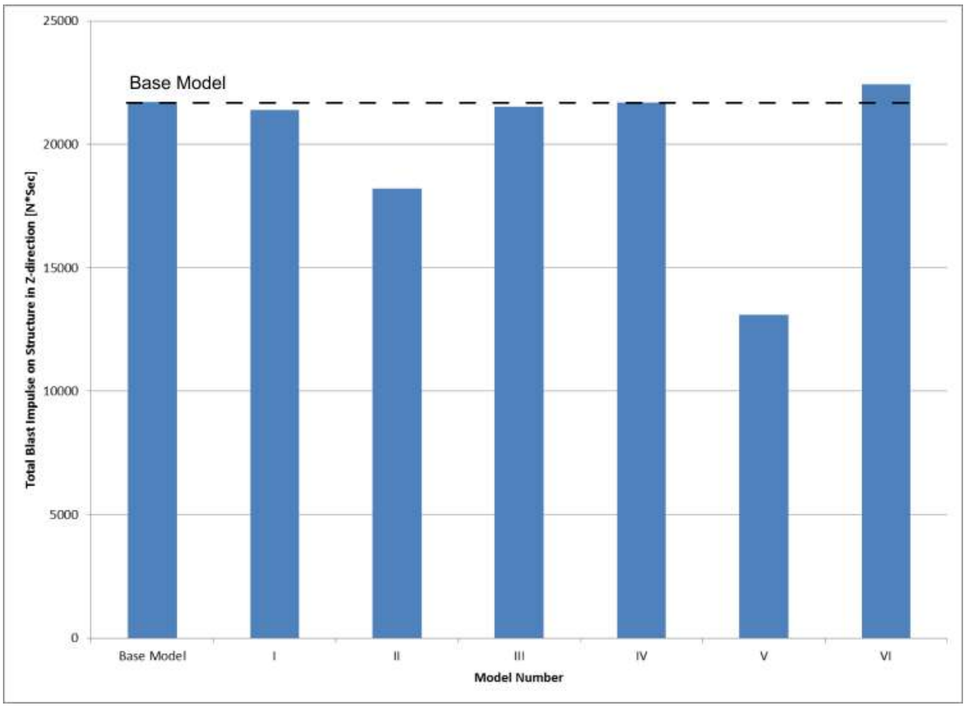
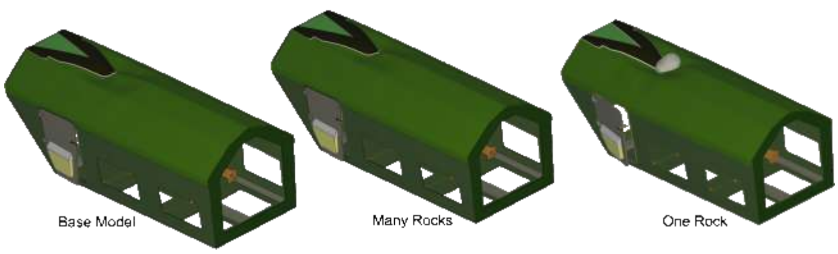


Figure 34 Deformed structure for the Base Model, model II and model V (see online version for colours)



6 Conclusion

Over 80 simulations were performed to generate a design space for a buried mine blast event of the TARDEC Generic Vehicle Hull applying the IMPETUS Afea Solver®. Fourteen different design variables were considered both approach and process parameters. The response parameter chosen was the TBI on the structure in the global Z-direction. All 80 simulations ran to normal termination, illustrating the stability of the software over the estimated 1000+ computational hours. On an overall level, the trend in the results seems to match what was expected. The full investigated design space is shown in Table 2 where the values for the Base Model are highlighted.

Table 2 The full design space illustrating the values. The values for the Base Model are highlighted in bold

Variable	*Values*
Soil density [kg/m^3]	1370, 1620, 2020, **2301**, 2500, 3000
Packing routine	1 (dry: 1k), 2 (wet: 1k), **3 (dry, 10k)**, 4 (wet, 10k)
Inter particle stiffness [N/m]	1e+8, 2.5e+8, **5e+8**, 7.5e+8, 1e+9
Inter particle friction	0.05, 0.1, 0.2, **0.25**, 0.5, 0.75
Inter particle damping	Pack 3: **0.**, 0.005, 0.01 Pack 4: 0., 0.005, 0.01
Friction soil to structure	**0.**, 0.05, 0.1, 0.2, 0.3, 0.5
Soil domain size [m]	2 × 2 × 1, **3 × 3 × 1**, 3 × 3 × 2, 4 × 4 × 1, 6 × 6 × 0.5, 6 × 6 × 1
Charge size [kg]	6, **8**, 10, 15, 20, 30
Charge type	**C4**, TNT, Petn, m46
Geometry of charge	**Cylinder 1 : 3**, cylinder 1 : 1, sphere, box
Charge orientation [°]	**0.**, 22.5, 45., 67.5, 90.
Charge off centre location	**Centre**, close to centre, two outer positions
DOB [in]	0., 2., 3., **4.**, 5., 6., 8., 10., 12.
Total number of particles	500k, 1m, 2m, 3m, **4m**, 5m, 6m, 7m, 8m, 9m, 10m

For the soil related parameters it was seen that the TBI increased linearly with the density and that there was a small difference between the dry 10k soil packing routine and the dry 1k soil packing routine, whereas the difference in TBI for the dry and wet packing routines was around 5% for the current values. It was recommended to use the newer 10,000 particle packing routines since they are more accurate.

The soil bed was modelled with iDPM where there is a normal and a tangential spring (soil-to-soil stiffness) in the inter-particle contact as well as damping and tangential friction can be included. The sensitivity study on the stiffness showed that the value has little effect on the TBI when the soil-to-soil stiffness was changed within the same magnitude. It was suggested in general to use 5e+8 N/m for dry soil and 5e+9 N/m for wet soil. The soil-to-soil damping was tested for both the dry and wet 10k packing routines. In both cases the TBI decreased with increased damping coefficient. For the dry packing routine the TBI dropped by 2.7% going from the Base Model with no damping to an applied damping of 0.01.

The tangential inter-particle friction coefficient is one of the main parameters when calibrating the soil. The results were as expected, the TBI drops with an increase in the friction coefficient. In this case the difference in the TBI was 49% as the friction coefficient was increased from a value of 0.05 to 0.75. When the soil impacts the structure it can slide along the structure as it would in reality and so a friction coefficient for this contact can be specified. For the range of friction coefficients that were tested a nearly linearly relationship between the TBI and the friction coefficient was observed. The impulse increases with an increase in the coefficient and the increase was 6% between the maximum of 0.5 and no friction being applied, as is the Base Model case. This indicates a rather low influence from the friction between soil and structure when considering the TBI. The dimensions of the soil bed are often overlooked and an undocumented parameter in the buried mine blast literature which is why it was chosen here to be investigated. It was found that the 3×3 m x1 m soil bed that was used in the Base Model is the minimum dimensions for this set-up. Less height ($6 \times 6 \times 0.5$ m) gave a larger TBI, related to the use of a rigid reflected boundary at the bottom of the soil bed and a more narrow soil bed ($2 \times 2 \times 1$ m) gave a lower impulse, due to the lack of enough soil particles. The difference between the maximum and minimum TBI is 7% when including the $2 \times 2 \times 1$ m and $6 \times 6 \times 0.5$ m test cases and only 1.6% when excluding them. This shows that if the dimensions for the soil bed are realistic the change has little influence on the results.

Other design variables are related to the charge and one of the parameters considered was the size of the charge. All models ran to normal termination without any inverted elements, etc., even with the charge size of 30 kg and this was attributed to the robust nature of the ASET™ elements. The result shows that the TBI increases linearly with increased charge size. A study of the selected pre-defined HE types showed that Petn gives a larger TBI then C4 and TNT, where the latter gave the smallest impulse of the three. Different geometries of the charge where also tested, showing that the cylindrical charge in the Base Model gave the largest TBI and a sphere gave a much lower impulse. The cylindrical charge in the Base Model was rotated over a range from 0° (horizontal) to 90° (vertical) to demonstrate the effect on the impulse. Changing the charge to the vertical position resulted in a drop of 18% in the TBI compared to the horizontal orientation, which shows that the charge orientation does indeed matter. An even larger influence was seen when the charge was placed at different locations but with the same DOB. The TBI dropped as the charge was moved away from the "under belly" position used in the Base Model. The maximum drop is ~45% for the chosen configurations. Different settings of the DOB were also tested and it was found that a DOB of 4–6 inches resulted in the maximum TBI on the structure and lower impulses were obtained for both deeper and shallower buried mines. The smallest impulse was for a charge located flush with the soil surface which differs by 17% from the maximum impulse obtained but in this case air should probably be included as it plays a role for this situation.

When using the iDPM to model the buried mine blast event, the total number of discrete particles has to be specified by the user. In the Base Model this was selected to be 4,000,000 particles and a large number of different settings were tried. The largest number of particles tested was 10,000,000 which gave a 5% lower TBI than the Base Model, 0.5% lower than 8,000,000 and 2.5% lower impulse than using 6,000,000 particles. A very clear converge is observed with increasing number of particles which was expected.

With the knowledge obtained from the sensitivity test, a simulation of a realistic shaped IED was carried out. It was chosen to model an oil can that had the same amount of HE as the Base Model. The results showed that there were insignificant differences between the TBI on the structure in the oil can case and the cylindrical shaped 1 : 3 charge applied in the Base Model. Research in non-homogeneous soil beds was also carried out. A total of six different scenarios with embedded rocks were modelled, ranging from many small rocks to a single 47 kg rock placed in different locations. Two of them were significantly different when the TBI of the structure was compared. These were the scenarios with many rocks and the single rock placed above the HE with the latter having the largest difference compared to the Base Model. It had only 60% of the TBI obtained with the Base Model. However, the damage of the Hull was most extreme with this one rock formation which is an important observation.

The research presented here covered a large range of possible scenarios for buried mine blast events and it is the authors hope that the knowledge obtained from this study can be helpful both in understanding the physics but also as a guide to numerical modelling. Understanding trends that result from adjusting parameters such as the shape of the buried mine or it's orientation, the effect of soil friction to accurately calibrate a soil model, etc. provides useful information when developing a model., Different blast test sites can have vastly different soil beds and it would be interesting to carry out a calibration of these soils on simple blast tests of rigid plates and then apply the different soils to the TARDEC Generic Vehicle Hull Model. Other areas of research considered for future work is the investigation of: the effect of multiple charges, include the IMPETUS Blast ATD and multiple layered Soil Beds.

References

Anderson Jr., C.E.T, Behner T. and Weiss, C.E. (2011) 'Mine blast loading experiments', *International Journal of Impact Engineering*, Vol. 38, pp.697–706.

Anderson Jr., C.E.T., Behner T., Weiss, C.E., Chocron, S. and Bigger, R.P. (2010) *Mine Blast Loading: Experiments and Simulations*, Southwest Research Institute Report 18.12544/011, Contract # W56HZV-06-C-0194 for US Army RDECOM-TARDEC.

Assaf, Z., Ran, E., Golan, G., Drori, O. and Katalan, I.K. (2014) 'The influence of soil conditions on the blast intensity for sand clayey sand and gravel with silt', *Proceedings of the 28th International Symposium on Ballistics,* Atlanta, GA, 22–26 September, pp.1623–1633.

Belytschko, T., Wing, K.L. and Moran, B. (2000) *Nonlinear Finite Elements for Continua and Structures*, John Wiley & Sons Ltd., West Sussex, England, ISBN 0-471-98774-3.

Bergeron, D., Walker, R. and Coffey, C. (1998) *Detonation of 100-Gram Anti-Personnel Mine Surrogate Charges in Sand: A Test Case for Computer Code Validation*, Defense Research Establishment Suffield Report No. 668, October 1998.

Bergeron, D.M. and Tremblay, J.E. (2000) 'Canadian research to characterise mine blast output', *Proceedings of 16th International MABS Symposium,* Oxford, UK.

Børvik, T., Olovsson, L., Hanssen, A.G., Dharmasena, K.P.H.H.H. and Wadley, H.N.G. (2010) 'A discrete particle approach to simulate the combined effect of blast and sand impact loading of steel plates', *Journal of the Mechanics and Physics of Solids*, Vol. 59, pp.940–958.

Caippi, R.L. (2016) *Standard Operating Procedure for Simulating Underbody Blast (UBB) to Support Live-Fire Test and Evaluation with Arbitrary Lagrangian-Eulerian-Based Loading*, August, US Army Research Laboratory, ARL Report ARL-CR-0804.

Ehrgott, J.Q. (2010) *Tactical Wheeled Vehicle Survivability: Results of Experiments to Quantify Aboveground Impulse*, US Army Corp of Engineers Final Report ERDC/GSL TR-10-7, March.

Ehrgott, J.Q., Akers, S.A., Windham, J.E., Rickman, D.D, and Danielson, K.T. (2011) 'The influence of soil parameters on the impulse and airblast overpressure loading above surface-laid and shallow-buried explosives', *Shock and Vibration*, Vol. 18, pp.857–874.

Fiserova, D. (2006) *Numerical Analyses of Buried Mine Explosions with Emphasis on Effect of Soil Properties on Loading*, PhD Thesis, Cranfield University.

Gharababaei, G., Darvizeh, A. and Darvizeh, M. (2010) 'Analytical and experimental studies for deformation of circular plates subjected to blast loading', *Journal of Mechanical Science and Technology*, Vol. 24, No. 9, pp.1855–1864.

Grujicic, M., He, T., Pandurangan, B., Bell, W.C., Roy, W.N. and Skaggs, R.R. (2009) 'Development, parameterization, and validation of a visco-plastic material model for sand with different levels of water saturation', *Proc. IMechE Vol. 223 Part L: J. Materials: Design and Applications*, pp.63–81.

Grujicic, M., Yavari, R., Snipes, J.S. and Ramaswami, S. (2013) 'Extension of a current continuum-level material model for soil into the low-density discrete-particle regime', *Journal of Materials Engineering and Performance*, Vol. 22(2) *May*, 2013, pp.1268–1283.

Holloman, R.L., Deshpande, V. and Wadley, H.N.G. (2015) 'Impulse transfer during sand impact with a solid block', *International Journal of Impact Engineering,* Vol. 76, February, pp.98–117.

icasualties.org (2017) http://www.icasualties.org (Accessed 14 December, 2017).

IMPETUS Afea Solver, Online User Manual (2018), http://www.impetus-afea.com (Accessed 15 May, 2018).

Jensen, M.R. (2014) *The IMPETUS Afea Solver® – Verification Manual: Defense*, CertaSIM report, CS-0021-120114.

Jensen, M.R. (2017) *The IMPETUS HYBRID III 50th Percentile Male Blast, A.T.D.*, CertaSIM Report # CS-0052-09012017.

Jensen, M.R., Durocher, R. and Bouamoul, A. (2018) 'Finite element modeling of mine-blast events applying different approaches and comparison with impulse frame target experiments', *To be Submitted to International Journal of Impact Engineering,* 2018.

Jensen, M.R., Hause, T.J. and Vunnam, M.V. (2016) 'Calibration, verification and numerical sensitivity study of high explosive in buried mine blast events', *Proceedings of 2016 Ground Vehicle Survivability Training Symposium (GVSTS)*, Ft. Benning's Maneuver Battle Lab in Columbus, Georgia, 16–17 November.

Jensen, M.R., Honaker, M. and Boglaev, A. (2017) 'Calibration and verification of detailed hybrid III 50th percentile male anthromorphic test device (ATD) based on extensive mine blast tests', *Proceedings of 2017 NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS)*, 8–10 August, Novi, Michigan.

Leonards, G.A. (1965) *Experimental Study of Static and Dynamic Friction Between Soil and Typical Construction Materials*, Technical Report Air Force Weapons Laboratory issue AFWL-TR-65-161.

Mindle, W.L., Gasbarro, M. and Olovsson, L. (2014) 'The discrete particle approach to modeling air, soil and HE for blast simulations', *Proceedings of the 2014 Ground Vehicle Systems Engineering and Technology Symposium (GVSETS)*, 12–14 August, 2014, Novi, Michigan.

NATO Standardization Agency (2011) *Procedures for Evaluating the Protection Level of Armoured Vehicles – Volume 2: Mine Threat*, August, AEP-55, Volume 2 (Edition 2).

NATO Standardization Agency (2012) *STANAG 4569 (Edition 2) – Protection Levels for Occupants of Armoured Vehicles*, 18/12/2012.

NATO Standardization Agency (2014) *Procedures for Evaluating the Protection Level of Armoured Vehicles – Volume 3: IED Threat*, AEP-55, Edition C Volume 3 (Part I), Version 1, Ratification Draft 1.

Pickering, E.G., Yuen, S.C.K., Nurick, G.N. and Haw, P. (2012) 'The response of quadrangular plates to buried charges', *International Journal of Impact Engineering*, Vol. 49, pp.103–114.

Rasico, J., Jensen, M.R. and Newman, C. (2016) 'Modeling fragmentation of a 155mm artillery shell IED in a buried mine blast event', *Proceedings of 2016 NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS),* 2–4 August, Novi, Michigan.

Reincke, J.D., Snyman, I.M., Ahmed, R. and Beetge, F.J. (2008) 'A safe and secure, S.A.: blast characterization though impulse measurements', *Proceedings of 2nd CSIR Biennial Conference, CSIR ICC*, November, Pretoria, South Africa.

Snyman, I. and Reinecke, J.D. (2006) 'Measuring impulse from an explosive charge', *Proceedings of Ballistics Symposium South Africa, Denel-OTB*, Bredasdorp, 15–16 August.

Wadley, H.N.G., Boervik, T., Olovsson, L., Wetzel, J.J., Dharmasena, K.P., Hopperstad, O.S. and Deshpande, V.S., Hutchinson, J.W. (2013) 'Deformation and fracture of impulsively loaded sandwich panels', *Journal of Mechanics and Physics of Solids,* Vol. 61, pp.674–699.

Williams, K. and McClennan, S. (2002) *A Numerical Analysis of Mine Blast Effects on Simplified Target Geometries: Validation of Loading Models*, DRDC Valcartier TM 2002-260.

Zeleznik, T., Miiller, M., Eridon, J. and West, J. (2015) 'Analysis of craters from large buried charges', *Proceedings of 2015 NDIA Ground Vehicle Systems Engineering and Technology Symposium (GVSETS),* 4–6 August, Novi, Michigan, USA.